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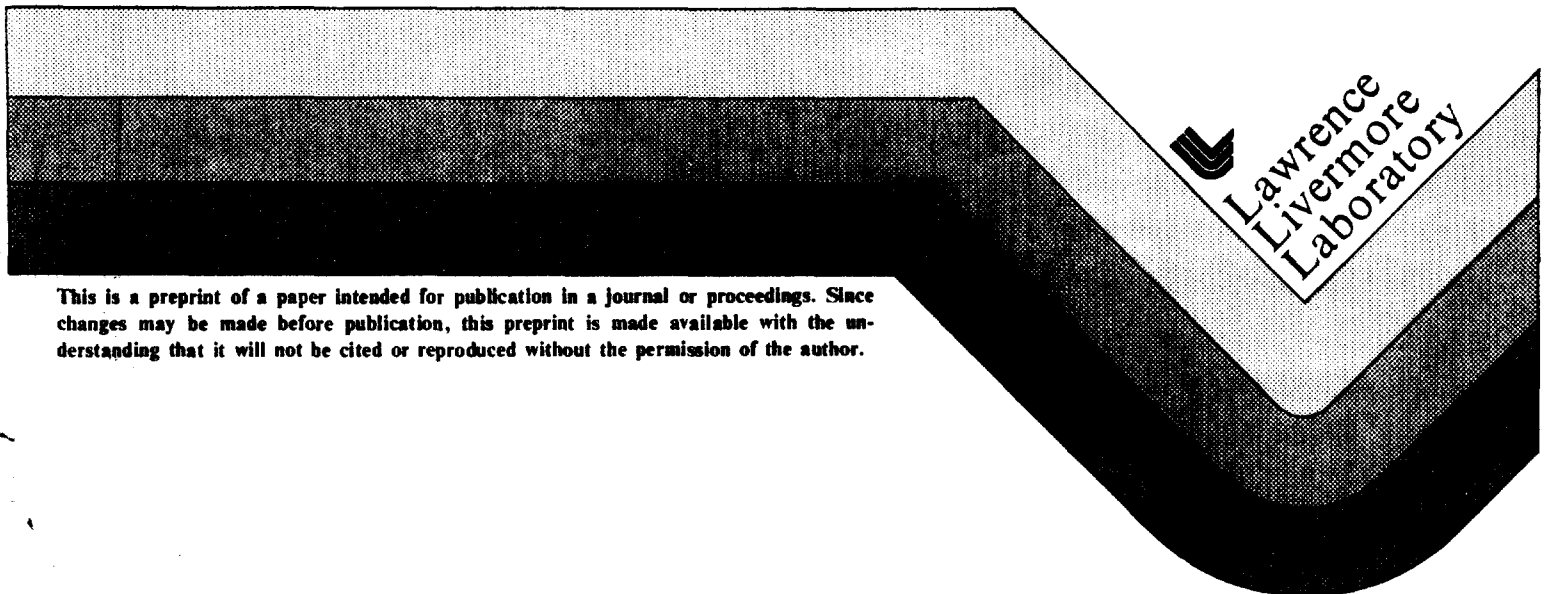
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APPLICATIONS OF INTELLIGENT MEASUREMENT SYSTEMS IN  
CONTROLLED FUSION RESEARCH

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*C. Owens*

APPLICATIONS OF INTELLIGENT MEASUREMENT SYSTEMS IN  
CONTROLLED FUSION RESEARCH

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## Contents

1. The Status of Controlled Fusion Research.
2. The Mirror Fusion Test Facility.
3. The Control and Instrumentation System.
4. The Supervisory Control and Diagnostics System.
5. The Control Room.
6. The Local Control and Instrumentation System.
7. The Local Control and Monitoring System.
8. The Magnets.
9. Protection of the Magnets.
10. Detection of a Threat to the Magnets.
11. The Control and Monitoring System for the Magnets.
12. The Programmable Controller.
13. Engineering Management and Design Procedures.

### Abstract

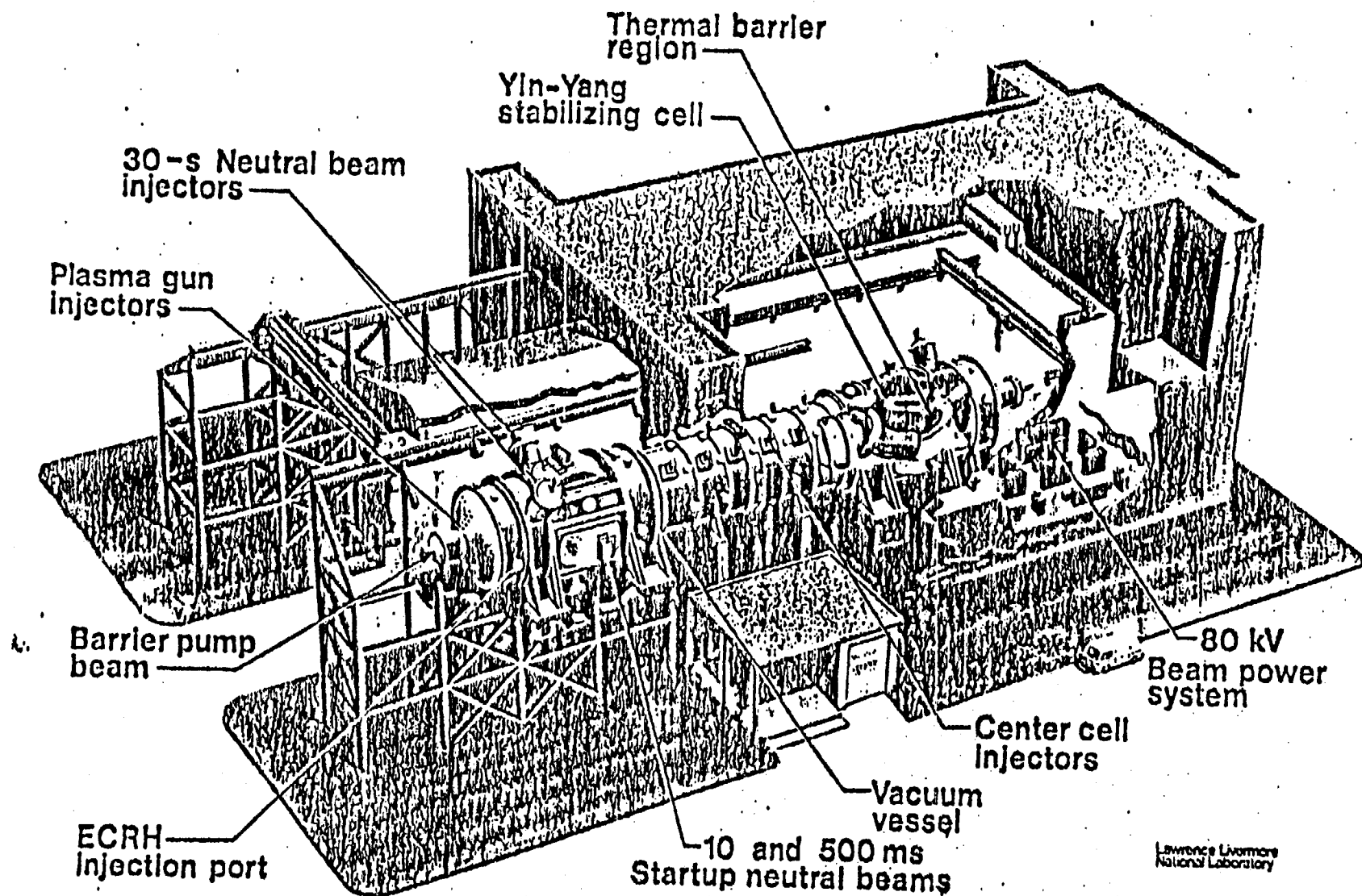
The paper describes the control and instrumentation for the Mirror Fusion Test Facility at the Lawrence Livermore National Laboratory, California, USA. This large-scale scientific experiment in controlled thermonuclear fusion, which is currently being expanded, originally had 3,000 devices to control and 7,000 sensors to monitor. A hierarchical computer control system, is used with nine minicomputers forming the supervisory system. There are approximately 55 local control and instrumentation microcomputers. In addition, each device has its own monitoring equipment, which in some cases consists of a small computer. After describing the overall system a more detailed account is given of the control and instrumentation for two large superconducting magnets.

## 1. THE STATUS OF CONTROLLED FUSION RESEARCH

Although controlled nuclear fusion (Kammash 1977) is not expected to play a role in electric generation for twenty years or more, the development of fusion reactors is now at an exciting stage. Scientific feasibility is no longer a question, the problem is how to make fusion a competitive source of energy. In the United States, fusion research, using magnetic confinement of the plasma, has followed two tracks: development of tokamak machines, and development of mirror machines (Coffman et al. 1979).

At the Lawrence Livermore Laboratory, the site of the principle mirror fusion effort, a series of mirror machines have been built and operated. They include Baseball, 2xIIB, Beta II and TMX. Just prior to construction of TMX (Tandem Mirror Experiment) a simple large scale mirror facility MFTF (Mirror Fusion Test Facility) was proposed (Coensgen 1976) and approved and has been under construction since 1977. The tandem concept appeared so attractive, that the MFTF project was redirected in 1980, and renamed MFTF-B (Thomassen and Karpenko 1980). MFTF-B is scheduled for completion in early 1985 and will provide a large scale experimental facility (see Figure 1) for investigating both the engineering and physics aspects of a large tandem mirror machine. Though MFTF was redirected, much of the original hardware will be completed as originally designed and operated in the fall of 1981 to demonstrate several areas of technology which include: superconducting magnets, cryogenic vacuum systems, high energy neutral beams and remote computer control and instrumentation of the facility. This paper describes the MFTF computer control and instrumentation system.

# MFTF-B TANDEM MIRROR FACILITY



## 2. THE MIRROR FUSION TEST FACILITY

The purpose of the MFTF is to allow experiments to be conducted on plasmas of larger size, higher density and temperature, and with longer confinement times than was possible in past experiments. The confining magnetic field is created by a pair of unusually shaped superconducting magnets that produce a field of 4T at the edge of the plasma and 2T at the center (Henning 1980). The mirror effect of the field gradient confines the plasma except for a small escape zone. The plasma reaction region is 60 cm in diameter by 1 m long. The magnets, which have a mean circumference of 18 m, are contained in a vacuum vessel 10 m in diameter by 18 m long.

An experiment is initiated by 60 plasma streaming guns that inject low energy electrons and ions along the magnetic field lines for 10 ms. Buildup of the plasma is accomplished in part by twenty 20 keV neutral beam sources that develop a total beam current of 1000 A for 10 ms. The sources inject neutral deuterium atoms through the magnetic field lines, heating the plasma and increasing its density. Fusion temperatures and densities are reached by means of another set of neutral beams, the sustaining neutral beams, which are generated by twenty-four 80 keV 80 A neutral beam sources operating for as long as a half second. In the technology demonstration project now scheduled, only three of the sustaining beam sources will be installed and operated.

The specifications for MFTF call for a "shot" as often as every five minutes for 16 hours a day. An experimental run was to last 13 weeks followed by a five week period for maintenance and reconfiguration.



### 3. THE CONTROL AND INSTRUMENTATION SYSTEM

The MFTF, as originally conceived, had approximately 3,000 devices to control and 7,000 sensors to monitor. In a single five minute experiment, four million bytes of data were to be collected. The control of a system of this complexity requires great attention to the man machine interface. Because of this and the prodigious volume of data, computers must be used.

The computer control and instrumentation system is organized in a three level hierarchical system (Ng, 1979). At the top of this hierarchy is the Supervisory Control and Diagnostic System (SCDS) consisting of a distributed computer system containing nine minicomputers. The supervisory system controls some 55 microcomputers that comprise the Local Control and Instrumentation System (LCIS). At the bottom of the hierarchy are the Local Control and Monitoring Systems (LCMS) consisting of the sensor and control interfaces and either hardwired controllers or small computers.

The environment in the vicinity of the fusion machine is a hostile one. Over the life of the experiment, approximately 10 years, the cumulative effect of neutrons on insulation and semiconductors is appreciable. In addition to a large static magnetic field from the superconducting magnets, pulsed magnetic fields and electrical interference are caused by the startup and sustaining sources. The SCDS and LCIS systems are isolated from these effects by placing them in a separate control building some 75 m from the building housing the experiment. The LCMS are, of necessity, intimately connected to the experiment. Communication between the LCMS and the control building is in the form of digital signals carried over fiber optic cables. Fiber optics are immune to electrical and magnetic interference and, in addition, electrically isolate the computer equipment in the control room from the outside environment (Trover, 1981).

#### 4. THE SUPERVISORY CONTROL AND DIAGNOSTICS SYSTEM

The Supervisory Control and Diagnostics System (SCDS) is a distributed computer system that monitors the state of the apparatus, controls the experiment, and collects and processes the data (McGoldrick 1979, Butner 1979). It consists of nine 32 bit minicomputers connected in a star configuration through a shared memory of two 128 kilobyte units as shown in Figure 2. Each computer has either a ten megabyte disk or an 80 megabyte disk. In addition, there is a 300 megabyte disk, two tape drives, and an array of terminals and printers. Two of the computers are used for database management and experimental diagnostics data processing and seven are used for the control and monitoring of the apparatus. In a five minute experiment cycle, the SCDS system will allow the operator to setup and fire a shot after which it collects about four megabytes of data, and performs an intershot analysis.

Several important considerations have governed the design of the supervisory system. Change is an essential element of the experiment, consequently the system must be flexible and easily altered. Reliability is also important. The system is designed so that a single point failure of the computer hardware does not prevent the execution of an experiment. At most, a failure causes a five minute delay.

The cost of meeting the reliability requirement by simple duplication of computers is too great, consequently, a more subtle approach is employed. Each machine has a backup machine designated from among the eight other machines. Switches on the data buses allow the buses to be connected to either the primary machine or its backup.



In the supervisory system, related tasks are grouped together in units that are as self-contained as possible (Wade and Choy, 1979). Each is thought of as a logical or virtual machine that maps onto a actual machine. In this way, the software development is made independent of hardware considerations.

Each machine has immediate access to a portion of the shared memory that connects the nine computers. When a computer completes a task a checkpoint is placed in the shared memory. If a failure occurs, these checkpoints are used to transfer control in a smooth manner. The shared memory is used to record data and setpoint information - not programs, each machine stores its own programs. Information can be read from the shared memory, but to protect the integrity of the data, incoming data is processed by a centralized database management system.

Use of a centralized database management system has several advantages. Since the data is recorded in only one place, there is greater consistency than there would be if every computer had its own database system. Memory requirements are also reduced. In addition, a well thought out system simplifies programming.

The database management system insulates the user from the necessity of thinking in terms of the machines needs and allows him to operate on the data in a more natural way (Choy and Wade, 1979). The user accesses the database management system in one of two ways: the program level interface or the query level interface. The program level interface is used by programs to access the database. These programs are written in Pascal but use a special database syntax developed for SCDS. A precompiler expands this syntax to one that can be compiled by a Pascal compiler. The query level interface is employed by operators using terminals as described in the next section.

## 5. THE CONTROL ROOM

The man-machine interface of the MFTF combines the best of human engineering with the latest computer technology (Speckert, 1979). The control room was designed from fundamental principles to ensure operator comfort and to facilitate the communication of a large amount of information in a short period of time. Adaptability to change and reliability were also important considerations.

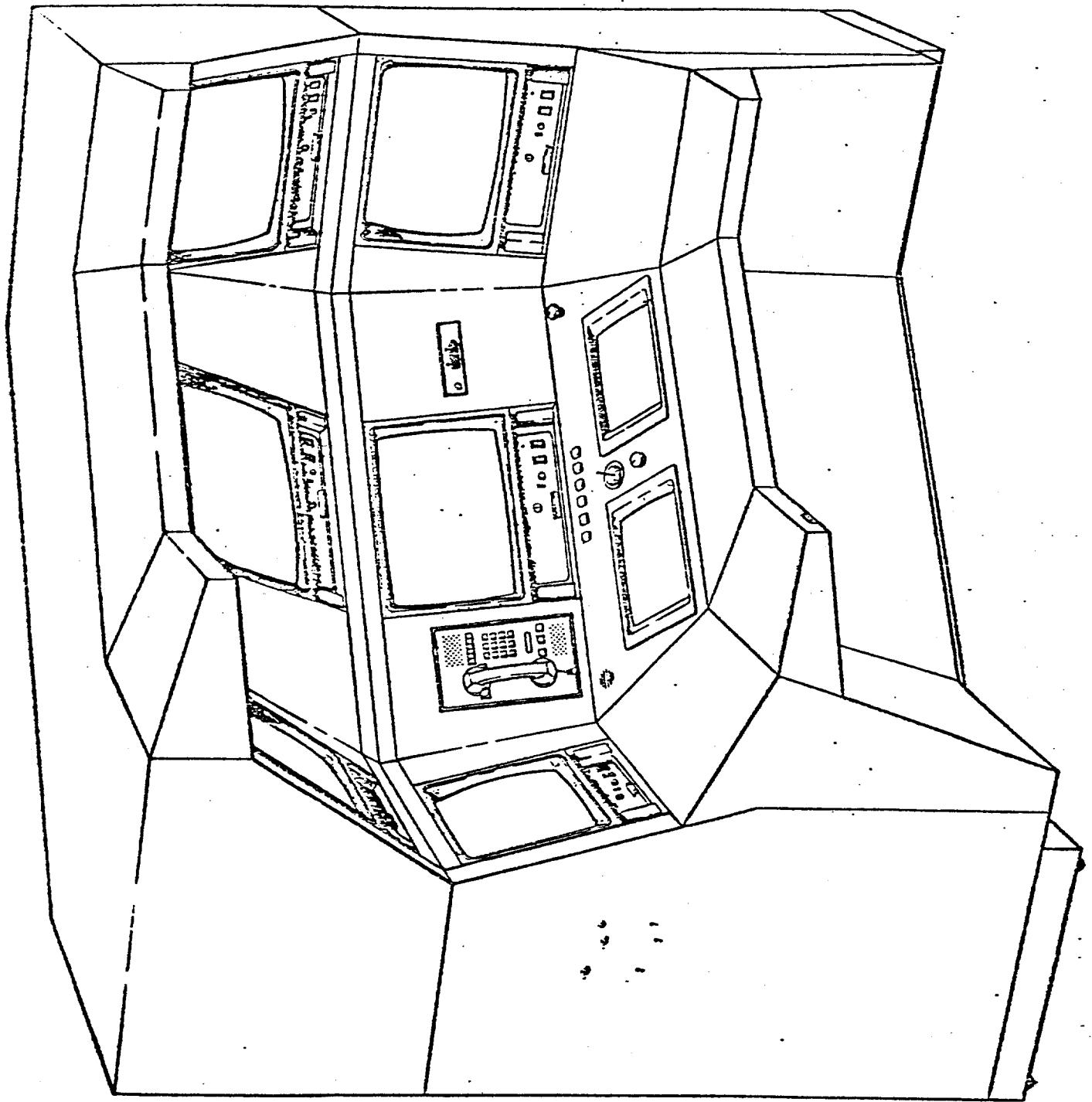
The experiment is controlled from seven consoles located in the control building. There are almost no hardwired switches or displays, the control is entirely through software generated displays.

Two kinds of cathode ray tube monitors are used, a status screen and a touch panel screen. The status screen is a 19-inch (48.3 cm) color monitor, the touch panel is a 13-inch (33.0 cm) color monitor covered with a transparent touch sensitive grid.

The control room contains five subsystem consoles and two supervisory consoles. A subsystem console has three status screens and two touch panels, a supervisory console, which is shown in Figure 3, has six status screens and two touch panels. An operator selects a software generated display or calls for information by means of structured menus on the touch panel. A selection is confirmed both visually and audibly.

Status information can be viewed from any console, but only one console has control of a process. However, control is easily passed between consoles so that the system can tolerate the failure of a console (Nowell, 1979).

FIGURE 3



## 6. THE LOCAL CONTROL AND INSTRUMENTATION SYSTEM

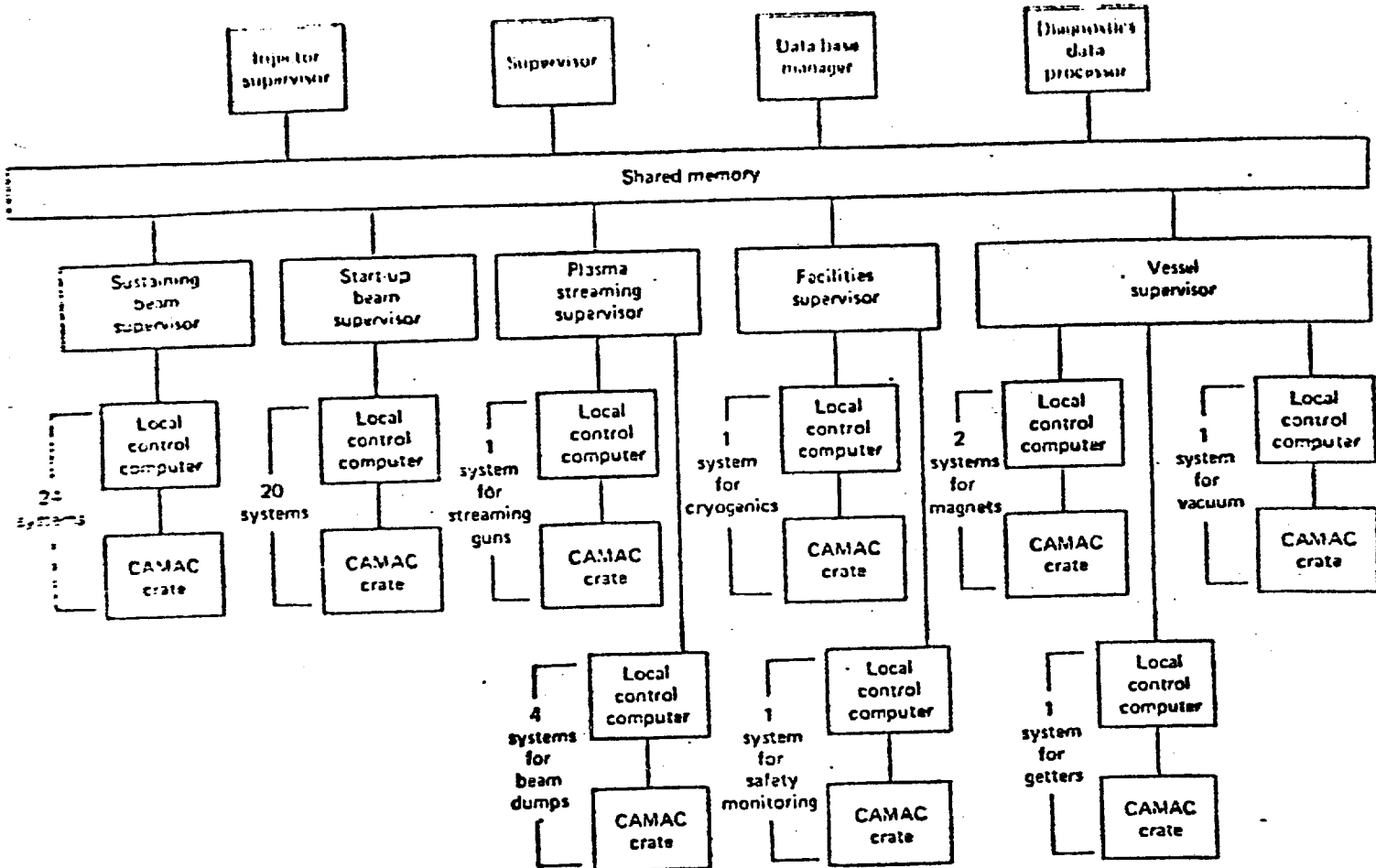
In the hierarchical computer control system, the Local Control and Instrumentation System (LCIS) lies between the Supervisory Control and Diagnostics System and the Local Control and Monitoring Systems. The LCIS consists of 55 microcomputers controlling nine different subsystems as shown in Figure 4 (Labiak, 1979). The microcomputers, which are LSI 11/2 computers with 32 kilowords of memory, are located in the remote control building adjacent to the SCDS computers.

A typical local control system is shown in Figure 5. Communication with the SCDS system is through a standard, 9600 baud, serial, full duplex, asynchronous channel based on the RS 232C standard. The channel contains four control lines used for handshaking. Errors are detected by a parity check and by a 16 bit checksum that follows each message.

The LSI-11's are connected to the experiment by fiber optic links, which are as much as 250 m long. Standard CAMAC equipment is used wherever possible. A CAMAC serial highway driver provides the interface between the computers and the fiber optic cables. At the experiment end of the fiber optic link, the devices are interfaced through CAMAC crates. In general, each group of sensor or control devices requires a unique crate configuration.

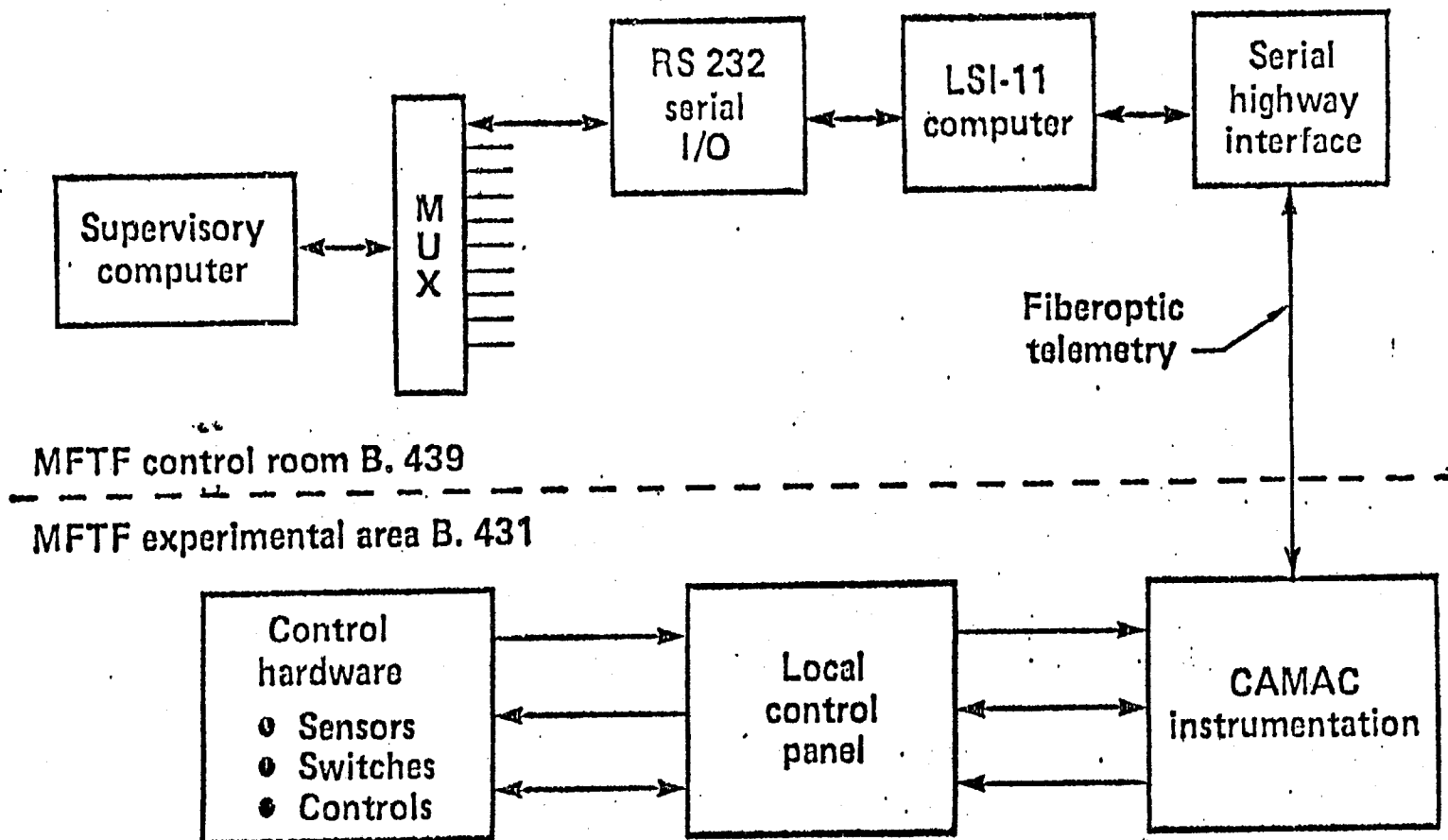
In as much as is possible, the same software is used for all of the LCIS computers (Lau, 1979). The communication link with SCDS and the CAMAC serial highway is identical for all of the computers. In addition, each LSI-11 has the same system executive, a system developed in assembly language. The operating programs, which are unique to each task, are written in Pascal.

FIGURE 4





## TYPICAL LOCAL CONTROL SYSTEM



-12-

FIGURE 5

## 7. THE LOCAL CONTROL AND MONITORING SYSTEM

The Local Control and Monitoring System (LCMS) has two functions: to provide a control and monitoring interface between the apparatus and the remotely located computers of the control and instrumentation system, and to provide a means for local control of the equipment. Local, manual control is necessary during initial checkout, and for subsequent maintenance and troubleshooting.

Tailored as they are to the individual needs of the devices they control, the local control and monitoring systems have a variety of configurations. The magnet system and the safety monitoring system are based on small computers. The following sections describe the local control for the magnet in greater detail.

## 8. THE MAGNETS

Before describing the control and monitoring of the magnets it is necessary to give a brief description of the magnets themselves and of some of the problems encountered in operating and protecting large superconducting magnets.

The magnets (Henning 1979, 1980) consist of a pair of unusually shaped magnets, dubbed a yin-yang pair, wound with a niobium-titanium superconducting conductor embedded in a copper matrix. Each coil has an inductance of 11 H and an operating current of 5,775 A. Four hundred megajoules of energy are stored. The magnets are cooled to below 4.98 K by natural circulation of liquid helium. When the technology demonstration phase is complete, the magnets will become one of the ends of a much larger magnet system consisting of a similar pair and more than a dozen other superconducting magnets (Bulmar and Van Sant 1980).

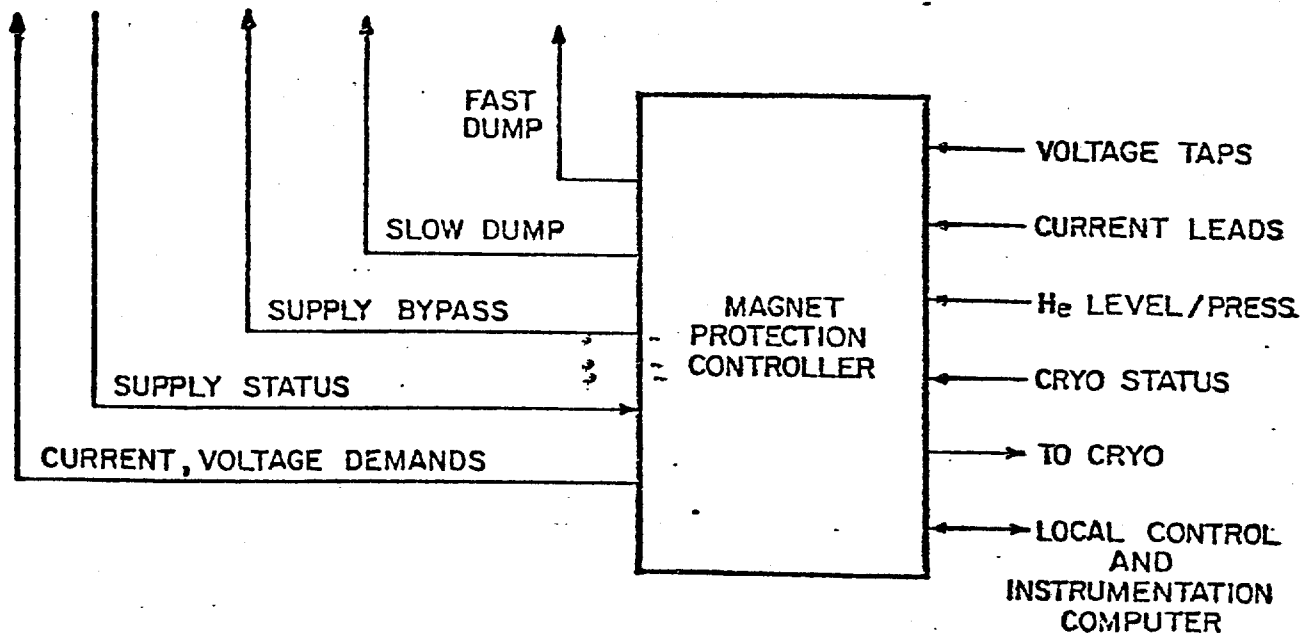
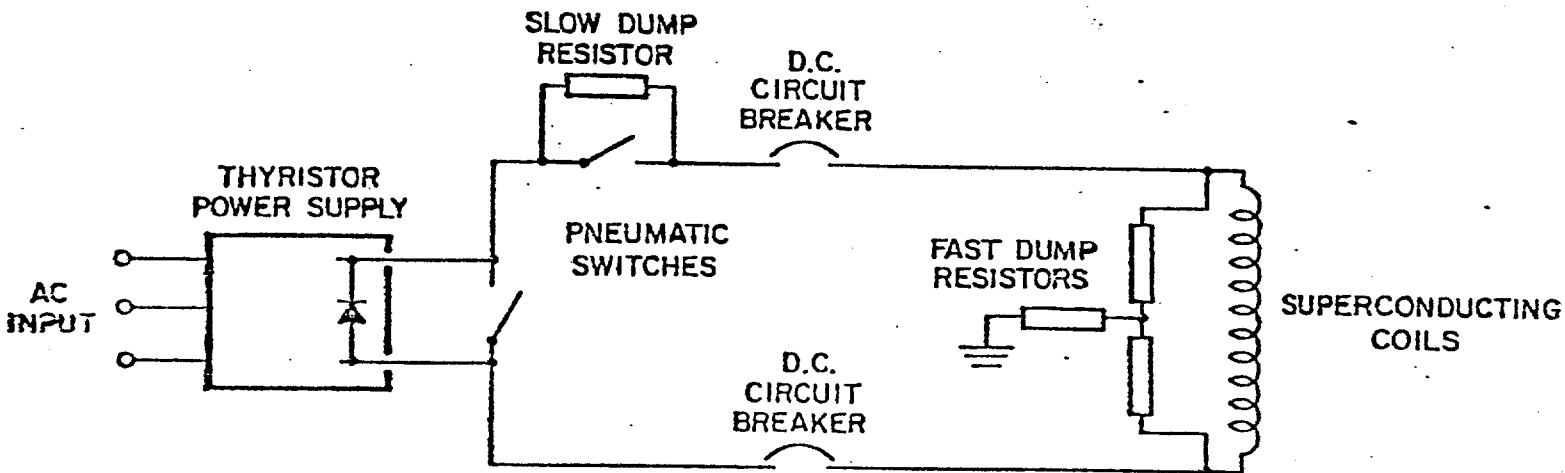
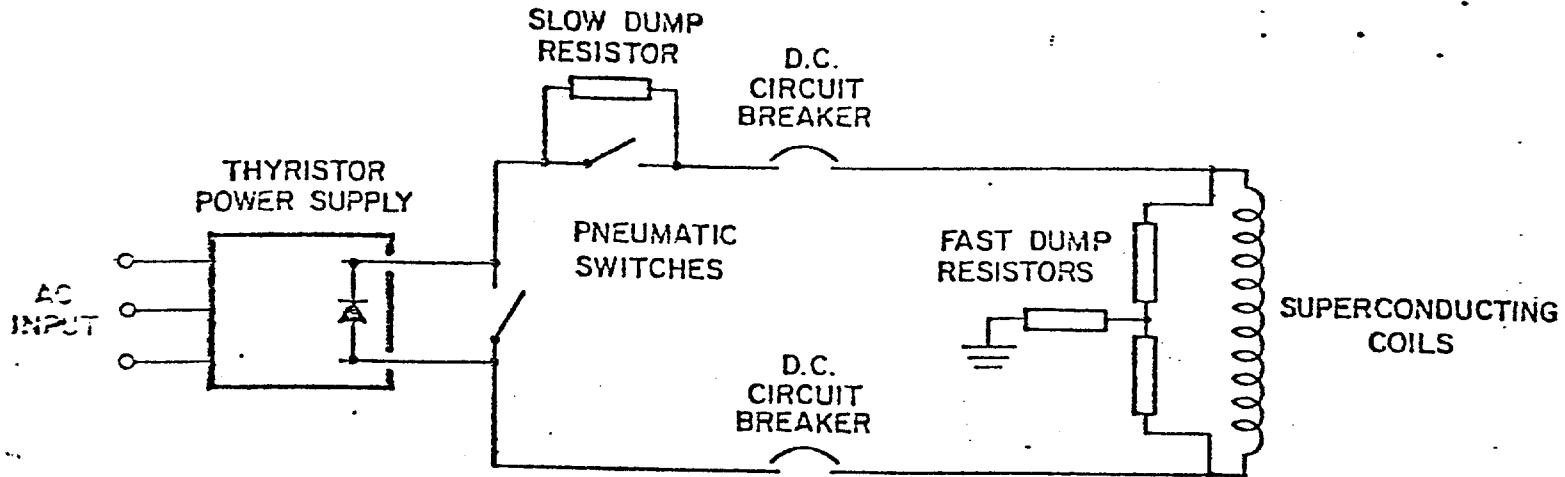
The magnets are supplied from a pair of 12 V, 6,000 A, thyristor controlled power supplies. During charging, the supplies operate in a voltage regulated mode; while the current is stationary they operate in a current regulated mode. They can also operate in a freewheeling mode, essentially acting like a short-circuit.

#### 9. PROTECTION OF THE MAGNETS

When fully charged, the magnets store an enormous amount of energy; energy, which in a mishap, could destroy the magnets themselves. Elaborate precautions are taken to prevent this possibility from occurring. If an emergency condition is detected, a substantial portion of the stored energy is transferred to a resistor in what is called a fast dump. The dump resistor is a high power resistor placed close to the magnet and connected permanently in parallel with it as shown in Figure 6. Ordinarily, current circulates through the magnet and the power supply. Opening the circuit breakers that connect the magnet to the power supply forces the current to flow through the dump resistor.

A fast dump places considerable electrical and mechanical stress on the magnet and is, therefore, used for only the most extreme fault conditions. Less dangerous conditions signal a "slow dump." In a slow dump, a small amount of resistance is placed in series with the power supply and magnet by opening pneumatically operated switches. Provision is also made for shorting the power supply, a procedure called a backup slow dump. A slow dump has a time constant of about two hours as compared with a time constant of 70 s for a fast dump.

FIGURE 6



#### 10. DETECTION OF A THREAT TO THE MAGNETS

The magnets cannot be repaired, consequently, it is of extraordinary importance to detect any condition that threatens their safety. The conditions measured, and the remedial actions are summarized in Table I.

Two conditions are especially threatening to the magnet: the formation of a growing normal or nonsuperconducting zone within the magnet's winding, and overtemperature at a magnet lead.

The magnet leads are potential trouble spots because it is here that the transition is made from room temperatures to the near absolute zero temperature of the magnet. The lead is a carefully designed thermal structure cooled by a controlled liquid helium flow and heated by external heaters. Abnormal conditions are detected in two ways: by measuring the lead temperature and by measuring the voltage drop across the lead.

Normal or nonsuperconducting portions of the winding can be generated by mechanical motion or by changes in the magnetic field. In theory, a growing normal zone should never occur. The magnet is designed with sufficient copper and cooling so that a normal zone is soon restored to the superconducting state. A growing normal zone means that for some unexpected reason the heat generated is excessive or the cooling is inadequate in a localized portion of the winding. If allowed to continue, the temperature could rise beyond acceptable limits, destroying the magnet.

Detection of a normal zone is not an easy matter. It is desirable to detect a normal zone one meter long, which at 6,000 A causes a resistive voltage of 23 mV. The self and mutually induced voltages are much higher, and even when the current is steady, large noise spikes are caused by mechanical motion and electrical interference. The induced voltages are balanced out by a set of resistive bridges placed across the coils and its voltage taps (Owen,

TABLE 1

Abnormal conditions in the magnet system and the action taken

<u>Fault</u>	<u>Action</u>		
	FAST DUMP	SLOW DUMP	HOLD
1. Growing Normal Zone ( 10m)	X		
2. Stable Normal Zone ( 10m)		X	
3. Current Lead Overheating			
Temperature Alarm Level 1		X	
Temperature Alarm Level 2	X		
4. Low Helium Level In Dewar		X	
5. High Helium Pressure In Dewar		X	
6. Valve from Helium Dewar Closes		X	
7. Main Vacuum Failure (Major)		X	
8. Guard Vacuum Failure (Major)		X	
9. LN <sub>2</sub> System Failure			X
10. Helium Refrigeration Failure			X
11. Magnet Protection Controller		X	
12. MFTF Computer or CAMAC Failure			X
13. DC Power Supply Failure		X	
14. Battery Charger Failure		X	
15. Inverter Failure		X	
16. 120 VAC Power Failure 1 Minute		X	
17. Inverter and 120 VAC Power Failure	X		
18. 120 VDC to Circuit Breaker Failure	X		
19. Failure in Current Lead Valve Control		X	

1980). The effect of short-term voltage fluctuations is reduced by a form of digital filtering in the monitoring system.

#### 11. THE CONTROL AND MONITORING SYSTEM FOR THE MAGNETS

A programmable controller, which is in fact a small computer designed for industrial use, is the central element of the magnets' control and monitoring system. A fiber optic link connects it to a remotely located LSI-11 that is part of the LCIS. It is connected to the sensors it monitors, and the devices it controls through modules supplied by the manufacturer. These modules include binary input and output ports and analog-to-digital and digital-to-analog converters.

The controller, which is shown schematically in Figure 7, has several tasks in addition to providing an interface with the LCIS computer. By means of a local control panel, it is used to operate the magnet power supplies and the protective instrumentation during initial checkout, maintenance, and troubleshooting. Charging of the magnets is initiated from the local control panel to ensure visual inspection of the area. In addition to detecting the two critical conditions, normal zones and current lead abnormalities, the controller monitors a large number of other conditions. The controller, which has a retentive memory, also stores a limited history of the magnets' condition which is available should the LCIS fail. A separate LCIS computer, which has no control function, collects a more comprehensive record of the magnets' operation.

Detection of a normal zone is the most critical function of the local system. There are three detector circuits, each consisting of two bridges spanning all or part of the coils, isolation amplifiers, and summing amplifiers that add the voltages according to the detector law. The detector

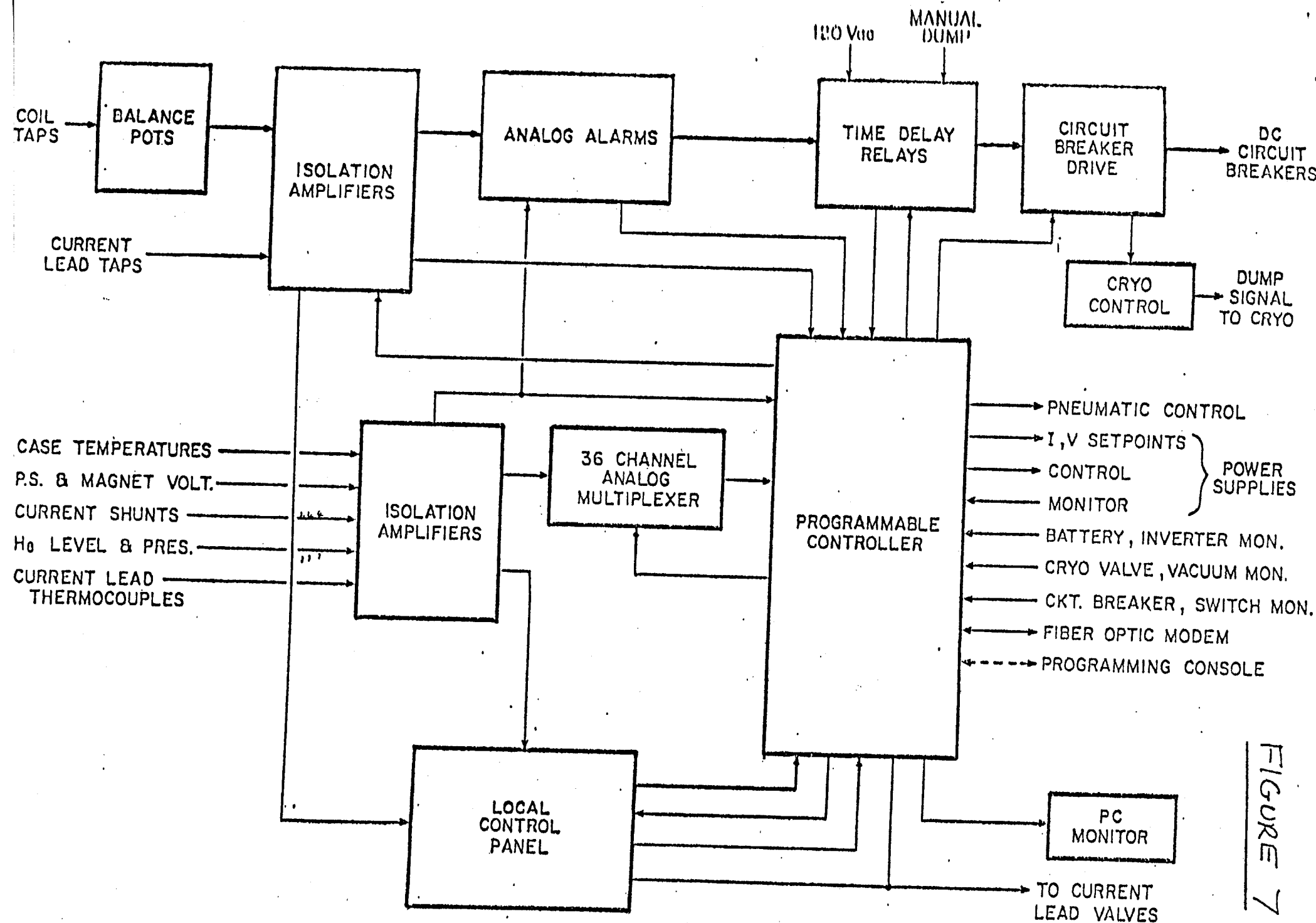


FIGURE 7



voltages are digitized and delivered to the programmable controller where they are processed. A fast dump is ordered if a detector voltage has exceeded an upper limit or if a lower limit is exceeded and the detector output is growing rapidly. Other conditions trigger a slow dump or a backup slow dump. Filtering is achieved by basing a decision on a number of samples rather than a single one.

There are two backups to the normal zone detector. To guard against failure of the detector bridges, the coil voltages are also monitored. The controller is supplemented by an all analog system, consisting of operational amplifier circuits and decision making circuits that make a calculation similar to that made by the programmable controller. Neither of these backups is as sensitive as the primary system.

Extensive reliability calculations were carried out using IEEE Standard 500-1977, Military Handbook 217C, and manufacturers' data. The mean time between erroneous fast dumps is estimated to be 13,000 hours. A dangerous normal zone would be missed only once every  $4.7 \times 10^9$  hours.

In addition to normal zone detection, a large number of measurements that bear on magnet safety are monitored by the programmable controller. These include the current lead status, the magnet case temperature, temperatures and pressures of the cryogenic and vacuum systems, and the status of the magnets' power supply. The controller even monitors itself, by means of an external device called a watchdog timer. If the timer does not periodically receive a signal from the controller it informs the LCIS.

In all, a total of 289 actively measured sensors and 43 standby sensors are used to monitor the state of the magnet and its associated cryo-vacuum systems. Strain in the core and conductor is measured by metallic strain gages. Temperature is measured by means of thermocouples, cryogenic linear

temperature sensors, glass carbon resistors, or manganin resistance thermometers, depending on the temperature range. The welds in the core are monitored by 72 crack detectors. These specially designed sensors consist of a number of parallel wires stretched over the weld at right angles to it. If a crack occurs one or more wires break, changing the resistance of the sensor.

## 12. THE PROGRAMMABLE CONTROLLER

Programmable controllers were originally intended as replacements for electromagnetic relays, but they have evolved into small computers that are specially adapted to industrial environments. The programmable controller selected for the magnet is a 16 bit, solid-state machine, based on a bit-slice integrated circuit microcomputer having 12,000 words of CMOS memory with battery backup. The input and output ports, which are supplied by the manufacturer, employ electro-optic isolators. Tests made at the Laboratory prior to purchase demonstrated that the controller would survive the hostile electrical, magnetic, and thermal environment of the experiment.

The controller is programmed using an augmented ladder logic language. A simple decision-making program takes the form of a diagram that resembles the circuit diagram of a similar relay circuit. Counters and timers are also available. The augmented functions, which are added to the diagrams, include the arithmetic operations, logic operations, and data modification and transfer operations, such as first-in, first-out registers. Programming in this language is similar to assembly language programming but in most cases, less time consuming.

Programs are entered into the controller by means of a microcomputer based soft copy terminal with a cathode ray tube display. A combination of software generated menus and keyboard function allows the user to construct

relay diagrams on the screen. Cassette tapes provide a variety of editing and programming facilities.

### 13. ENGINEERING MANAGEMENT AND DESIGN PROCEDURES

In a project as large and complex as MFTF, the smooth coordination of activities and the sure and rapid communication of information are vital. Through experience, a number of effective management and design techniques have been developed at the Laboratory.

A matrix organization is used. For administrative purposes, individuals are assigned to departments organized by professional specialities but work responsibility is organized along project lines. An engineer's responsibilities are clearly defined and often encompass the planning, design, manufacturing, test, and operational stages of a project.

Conventional engineering and manufacture is, whenever possible, done by outside contractors. The Laboratory concentrates its resources on new technology. For example, the magnet conductor was developed at the Laboratory and the first magnets were wound there. On the other hand, sustaining neutral beam sources, which have reached a satisfactory stage of development, were built by contractors.

Over the years, an effective design procedure that requires periodic review and group participation has evolved. At the very least, an engineer's work is subject to a preliminary and a final review by his peers. In most cases, the review procedure is more lengthy. For example, the design of the magnet control and protection system began with two workshops, a year apart, that assembled experts from all over the country. Two design reviews employing outside experts followed, in addition to several internal reviews of

the subsystems. A design review consists of a written and oral presentation by the project engineer and consumes a day or more.

Software is developed using similar procedures. In the development of the SCDS software the following steps were used: investigation, preliminary design, review, final design, review, implementation, test planning and programming, submission to the system librarian.

Complexity, frequent change, and urgency are characteristics of the project. At any given time, different parts of the apparatus are at various stages of completion, ranging from planning to test. Given these conditions, the allocation of resources and the scheduling of time are crucial problems. Computer aided analysis is used to generate schedules and identify critical items.

#### 14. CONCLUSIONS

In the past there was a distinct difference between instrumentation needed in industry and instrumentation used in scientific experiments. With the advent of large-scale experimental projects, such as MFTF, the gap between the two kinds of instrumentation has narrowed. MFTF has many of the attributes of a large industrial project. The lifetime is long, the environmental conditions are harsh, and the physical scale is large. At the same time industrial projects have tended to become more like scientific experiments. The ever increasing rate of technological change has reduced the lifetime of industrial plants and put a premium on flexibility and change. Therefore, much of what has been learned in the instrumentation and control of MFTF can be applied to industrial plants, in particular, to the design of power plants and chemical processes.

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CAPTIONS FOR THE FIGURES

Figure 1. An artist's conception of the MFTF tandem mirror test facility

Figure 2. The supervisory control and diagnostics computer system

Figure 3. A supervisory control console

Figure 4. The local control and instrumentation system

Figure 5. A typical local control system

Figure 6. The superconducting magnets, dump resistors, switches, and magnet  
protection controller

Figure 7. The inputs to and outputs from the programmable controller